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Development of a Hard-Patch Approach for Scarf Repair of Composite Structure

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ABSTRACT

The pre-moulded (hard) patch approach for scarf repair of composite structures has several advantages compared with the conventional prepreg lay-up (soft-patch) approach, which involves forming the patch directly in the repair cavity. These include the development of patch properties which match the parent structure; much improved patch geometry (no wrinkling or ply distortion) and, importantly for aircraft employing high temperature composites designed to operate at 177C/350F (such as JSF), reduced application temperature – depending on the repair adhesive chosen.

This report outlines a study aimed at developing this technology with potential for application on aircraft such as JSF.

RELEASE LIMITATION

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Development of a Hard-Patch Approach for Scarf Repair of Composite Structure

Executive Summary

The pre-moulded (hard) patch approach for scarf repair of composite structures has several advantages compared with the conventional (soft-patch) approach, which involves moulding patch directly in the repair cavity. Advantages include the development of patch properties matching those of the parent structure; much improved patch geometry (no wrinkling or ply distortion) and, importantly for aircraft with higher temperature requirements such as the Joint Strike Fighter (JSF), reduced application temperature, depending on the repair adhesive chosen.

This report outlines the development of this repair technology. An F/A-18 horizontal stabilator (HS) was chosen to develop and demonstrate approaches for hard-patch repairs as it is representative of most of the challenges likely to be encountered in applying scarf repairs to highly loaded primary structure. This component is made predominantly of carbon/epoxy; however, other than the higher adhesive-cure temperature for aircraft structures based on BMI composites, the requirements are similar.

CNC machining was the approach taken to form the scarf cavity in the HS. A solid model was developed for the CNC using ultrasonic measurements of skin thickness and probe measurements of curvature of the HS. The scarf patch was formed directly using a matched die mould CNC machined in aluminium alloy, using the solid model. The fit of the moulded hard patch into the machined cavity was found to be excellent. Following bonding the patch, the repair area in the HS was subjected to ultrasonic inspection and found to be free of voids and any other significant defects.

The high-temperature structural requirements for repairs to carbon/BMI composites are very challenging for candidate adhesives. The outcome is that the conventional ~ 3 ° scarf angle may not be low enough. Some methods of maintaining or even increasing the scarf angle are proposed in an appendix to this report.

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Dr Alan Baker prior to retiring from DSTO was Research Leader Aircraft Materials. On retiring he was given the honarary title of Emeritus Research Leader Aircraft Composite Structures. He continues to be involved in DSTO research in his specialist area through his current position as Program Leader in the CRC for Advanced Composite Structures.

Contents

1. Introduction

1.1 Aim of program

Adhesively bonded flush scarf or step-lap joints have the potential to meet the structural and operational requirements for repair of composite airframe [1]. The aim of the study described in this short report was to develop and demonstrate a semi-automatic technology for applying scarf repairs having superior mechanical properties to those produced using the traditional approach. A more comprehensive report on this study is provided in Reference [2], which is work undertaken by the CRC for Advanced Composite Structures in a joint project with DSTO.

The high-temperature structural requirements for repairs to carbon/BMI. composites are very challenging for candidate adhesives. The outcome is that the standard ~ 3° scarf angle may not be small enough. Some methods of maintaining, or even increasing the scarf angle to minimise removal of parent material, is proposed in an appendix to this report.

1.2 Background

A flush repair involves machining a tapered or stepped cavity into the parent structure then bonding the patch. The machining removes the damaged region and provides the required joint geometry for the repair.

There are several options for manufacturing and applying the patch:

a) **Soft Patch** – The composite patch is laid up from pre-preg in the repair cavity and co-cured with the adhesive at the same time as secondary bonding to the parent structure - this is the traditional approach.

b) **Hard Patch, Moulded** – The composite patch is pre-manufactured in a mould matching the machined cavity and OML (outer mould line) and secondarily bonded in a separate operation.

c) **Hard Patch Machined,** – The patch is CNC machined to the contour of the OML and cavity and then secondarily bonded in a separate operation. Options for the patch material include composite laminate, titanium alloy sheet laminate or solid titanium alloy.

d) **Semi-Hard Patch** – The patch is manufactured from a series of pre-cured composite laminates each containing several plies or titanium sheets, which are interleaved with adhesive and either pre-bonded or bonded during the patch bonding process.

The advantages and disadvantages of these approaches are listed in Table 1. Both the machined and moulded hard patch approaches are being studied and appear very promising; however, only progress with the moulded patch is discussed in this report.

The usual method for forming the scarf in the composite laminate is by using a hand-held pneumatic router or grinder. The accuracy and uniformity of the scarf and quality of the exterior finish relies exclusively on the skills of the operator and type of tools used. This procedure is particularly challenging when shallow scarf angles, typically 3° for repair of highly loaded structure are required.

There is obviously an incentive to identify or develop automatic or semi-automatic methods for machining the scarf. A CNC machine was used in this study. This approach has the major advantage that it produces an accurate cavity with a uniformly smooth surface. Importantly this approach does not depend on the manual skills of the repair technician. However, in the event that a CNC capability is unavailable or uneconomic then the development of a low-cost semi-automatic procedure is the subject of a follow-on study.

The CNC approach has another major advantage as the CAD-CAM data used to form the scarf can be used to machine the mould to be used for the manufacturing the moulded patch.

In the absence of a CNC capability an alternative low-cost method for manufacturing the mould is to take a composite or plaster-cast (splash) from the scarfed region and then make a mould from a counter cast from the splash, using a tooling resin or composite. This approach is also the subject of a follow-on study.

Although the CNC approach in this study was used mainly as a highly desirable baseline it could be a practical depot-level procedure for cutting scarfs in components that are removable from the aircraft – or even directly used on an aircraft if a light-weight, portable CNC system has or can be developed.

2. Test Component

The component chosen for this study was an F/A-18 horizontal stabilator (HS). Other than the obvious advantages of availability and removability, this component was chosen for two reasons:

A. It is typical of primary carbon/epoxy composite-skinned honeycomb-core construction used in military aircraft. Repair of the HS poses the required challenges as it is designed to a high strain ultimate and has a curved (aerofoil) section with significant skin thickness variation, both in the cordwise and spanwise direction.

B. A similar HS from an Australian aircraft was used in an earlier repair study in conjunction with the US Navy as part of the Composite Repair Engineering Development Program (CREDP).

2.1 Horizontal Stabilator Description

The F18 has two independently moveable HS surfaces for longitudinal and pitch control. Each HS has a symmetrical aerofoil section, Figure 1, with a surface area of 44 sq ft per side and an aspect ratio of 2.44.

The skins are made of AS4/3501-6 180°C curing carbon/epoxy bonded with adhesive FM300 to a full-depth 5056-H39 aluminium honeycomb core, which provides the shear path. The composite skins are bonded to a Ti-6Al-4V titanium alloy splice plate. The inboard and outboard ribs are also made of this alloy, as is the root rib which contains the drive horn and actuator lever. The HS is supported through the horn by a steel spindle attached to the airframe.

3. Previous History Australian F/A-18 Horizontal Stabilator

The study was based on an F/A-18 HS damaged in flight by fragment impact on the composite skin quite close to the spindle attachment point. This is a high strain zone which is deemed by the original equipment manufacturer (OEM) to be unrepairable. Whilst design ultimate strains in the HS are mostly around 3750 microstrain (με) the peak strain in this location is around 5200 με.

As no accepted repair scheme exists for such a highly strained region even in moderately thick primary structure, the opportunity was taken to undertake a feasibility study with the US Naval Aviation Depot at North Island, San Diego to establish if a scarf patch, applied using conventional technology, could provide an effective repair under these extreme loading conditions [3].

The important point in connection with this study is that a scarf repair was applied using the (conventional) soft-patch approach (Table 1).

The main problem experienced in patch application was the formation of wrinkles (Figure 2), due to ply movement, during consolidation; this is one of the major problems associated with the soft-patch approach. The wrinkling could have been reduced or even alleviated by more effective debulking prior to co-curing the patch. However, in the soft-patch approach if such a problem occurs the patch must be machined away and the repair repeated. In addition to wrinkling, distortion of the plies running along the scarf is anticipated. It is planned eventually to section this patch system for examination, along with the patch produced by the hard-patch approach – described later.

The manual method was used by USN for forming the scarf in the stabilator, involving use of a hand-held pneumatic router or grinder, Figure 3.

4. Development of the Moulded Hard-Patch Approach

4.1 CNC Machining of the Scarf

A 3-axis CNC machine was used for cutting the scarf. The facility had environmental controls, including dust extraction, and elimination of oil and other contaminants. The cutting tool designed to use in the CNC machine was a semi-spherical steel rod mandrel coated with industrial-diamond grit.

4.2 Development of the Solid Model for CNC Matching

Data on thickness, contour and curvature of the carbon/epoxy skin outer-mould line (OML) was required and used for development of the CAD "solid model" for the CNC machining.

To locate and plot the thickness distribution in the skin a 25 x 25 mm grid was drawn over the prospective repair region. The method to obtain laminate thickness was based on time of flight of an ultrasonic pulse, using a manual scanning ultrasound system (A-Scan.) An off-cut section of an old F/A-18 horizontal stabilator was used to calibrate the NDI equipment by comparing the ultrasonic thickness measurements with direct thickness measurements using a digital micrometer.

In order to acquire digital data on the surface contour of the HS in X-Y-Z coordinates a semi-spherical probe was fitted into the spindle on the CNC machine. The F/A-18 stabilator was clamped on top of the CNC bench and then, at each node of the grid, the operator manually directed the CNC machine and lowered the spindle until the end of the probe touched the surface of the component in the already marked grid. In the same operation, the references (tooling points) were assigned to the four corners of the grid.

The model thus created was a truncated cone with an oval base shape. The cone had a constant draft angle of 3° and at a maximum thickness of 3 mm, giving a total nominal size of 440 mm long by 331 mm wide. The intersection of the generator of the cone with the skin surface was not exactly 3° at all points because of the curvature of the surface; however, the difference in angle was less than 0.1°.

4.3 Machining the Scarf

The CAD-CAM cutting program was "loaded" into the CNC machine and the component was mechanically clamped to the CNC machine bench.

The cutting reference plane, orientation and starting point were established using the existing grid and the previously surface contour data acquired. The "cutting path" was an oval shape starting at the centre of the "damaged area" with a spiral concentric radially incremental step of 0.010".

The final contour of the cavity (perimeter) was not a regular oval shape (Figure 4). This was due to the irregular curvature of the surface and the variation of the skin thickness.

4.4 Manufacture of the Matched Moulds

Matched moulds were manufactured - the top mould simply representing the skin OML curvature and the bottom the scarf cavity. The mould (Figure 5) was manufactured in aluminium alloy 7075-T651 using the CAD-CAM data developed for cutting the scarf geometry in the HS.

4.5 Manufacture of Scarf Patch

4.5.1 Acquisition of the Ply Configuration

The ply orientation was obtained by a visual examination of the machined cavity. The 0° , 90° and + or - 45° plies are clearly identified by the pattern revealed on the machined surface. The ply drop offs are also are clearly visible as a discontinuity in the relevant carbon/epoxy ply (Figure 6).

4.5.2 Marking and Cutting Plies

The next step in the manufacture of the moulded hard patch was to manually cut each individual carbon/epoxy ply to the right size, shape and orientation. The outside contour (perimeter) of the tool scarf cavity was used as the reference line to develop the template for each layer.

The outside contour was digitally transferred to an Autocad ® CAD program and all the templates were developed with this software. In order to cut each individual layer in the carbon/epoxy pre-preg, the geometry of each ply was plotted in a Mylar sheet. Mylar is easily attached to and detached from the pre-preg layer, leaving minimal contamination (Figure 7).

In order align properly each individual template over the pre-preg, two reference lines were printed over this "master" template to be used as an indication for fibre orientation and position.

4.5.3 Patch Moulding

To produce a surface suitable for bonding the patch into the scarf cavity peel ply was incorporated into the patch surface. When peel ply is removed from the patch a fresh layer of fractured matrix resin is created, this helps to provide a good bond. However, to ensure good bonding this surface must also be abraded or grit-blasted prior to bonding.

The peel ply also simulates the adhesive layer thickness, ensuring a suitable sized gap is left between the patch and cavity for the adhesive.

Prior to commencing the lay-up process for the patch, the peel ply located (bonded) on top of the tool was marked at each single layer location (using a template) for further reference in the placement of the pre-preg.

The starting point for the lay-up is the centre of the patch cavity. The first layer (from the bottom of the cavity) was positioned in place and aligned using the reference points. As each layer was added, the ply stack was debulked at room temperature.

The moulded patch showed some distortion as expected from the ply unbalance along the scarf region, but was otherwise sound. Ultrasonic examination of the patch, using the procedure described later, indicated no significant porosity or delaminations.

4.6 Fit Up and Bonding of the Scarf Patch

The fit-up of the finished patch was evaluated using a simple vacuum-bag assembly as shown in Figure 8. It was found that fit up was excellent, with no gaps or distortion. The distortion of the patch is easily removed at RT under vacuum-bag induced pressure; furthermore, distortion would be considerably reduced at the patch-bonding temperature as residual stresses would be much lower at 120°C– they would have been zero at 180°C.

Following satisfactory evaluation of fit-up, the patch was lightly grit-blasted along the bonding surface and assembled with adhesive FM 300 under a conventional vacuum bag assembly, with thermocouples monitoring and controlling the cure cycle. Cure temperature was 2 hours at 120°C under a slightly reduced atmospheric pressure. The resulting repair region is shown in Figure 9.

Note that doubler plies were not included in the repair. However, they could have easily been pre-formed and co-bonded with the patch if required. Generally, a doubler is required to protect the scarf tips and improve tolerance to damage. In this application they were not included to demonstrate the fit and very low surface profile of the repair possible from the moulded hard-patch technique.

The repair region in the HS was then ultrasonically inspected using an AUSS 4.5 (Automated Ultrasonic Scanning System). As shown in Figure 10, the ultrasound image was highly satisfactory showing a defect free patch (as expected from a previous inspection prior to bonding) and no significant porosity in the bond line.

5. Conclusions

1. The hard-patch approach has numerous advantages over the conventional soft-patch approach for application of scarf repairs to highly loaded composite airframe components. These advantages include the ability to form a wrinkle-free patch with properties matching those of the parent material and to bond it to the parent structure at a temperature dictated only by the cure requirements of the adhesive.

2. A carbon/epoxy F/A-18 Horizontal stabilator was used as the component on which to conduct this development as it posed realistic challenges. Although the patch application temperature with epoxy-matrix composites is somewhat lower than that

required for carbon/BMI composites, this will have little impact on the applicability of the moulded hard-patch technology to these composites.

3. The technology developed was based on the use of CNC machining to produce the scarf cavity and the patch mould using data on skin thickness and curvature taken directly from the stabilator.

4. The fit of the resulting patch into the scarf cavity was excellent and subsequent ultrasonic inspection of the patch system showed it to be free of voids and other defects.

6. References

1 A.A. Baker, 'Joining and Repair of Aircraft Composite Structures' Chapter 14 in *Composites Engineering Handbook* 1997 P.K. Mallick (Ed) (Marcel Dekker).

2 D. Bitton, A Baker and I Hertzberg CRC-ACS Report TM 05080 Jan 2006

3 A.A. Baker, R.J. Chester, R.J. Hugo and T.C. Radtke, "Scarf Repairs to Highly Strained Carbon/Epoxy Structure", International Journal of Adhesion, 1999, Vol 19, pp 161 – 171.

Table 1 Comparison of various Scarf Patch options

Patch Options	Pros and Cons
Soft Patch ***(Composite pre-preg)***	• Simpler manufacture • Excellent conformity • Mould not required **BUT** • Patch properties will not match parent material • Needs HT cure (unless different composite system), skin disbond danger • Prone to wrinkles and ply distortion along the scarf, due to ply movement during consolidation • Prone to voids, under vacuum bag consolidation • No prior NDI possible
Hard Patch, Moulded ***(Composite)***	• Excellent quality patch, matches parent laminate • No distortion of plies • Prior NDI possible • Lower temperature application (adhesive control) • Out-of autoclave application feasible **BUT** • Requires a mould, open or matched • Longer to apply (extra process steps), higher cost • Some local warping may occur due to ply unbalance
Hard Patch, Machined ***(Composite)*** ***(Titanium alloy sheet laminate)*** ***(Titanium alloy blank*)**	• Excellent quality patch all as above **BUT** • Distortion and machining problems, composite patch • Residual stresses, metallic patch • Stiffness mismatch, solid metal patch • Requires NC machining
Semi-Hard Patch ***(Composite laminates)***	• Can cure at lower temperature depending on adhesive interleaf • Prior NDI possible (with difficulty) of individual layers • Flexibility depends on the sub-laminate thickness • No need for a mould **BUT** • Patch 'diluted' with adhesive layer, may need to alter lay-up to compensate (ideally need thin interleaving adhesive say .05 mm) • Tend to select thicker sub-laminates, compromising flexibility to conform to curved surfaces • Adhesive interlayers could have porosity or bonding problems • Matching ply configuration, ply drop offs and skin-thickness changes will cause problems • Will be more suited to step joint configuration rather than scarf • May have problems achieving full flush configuration due to patch dilution

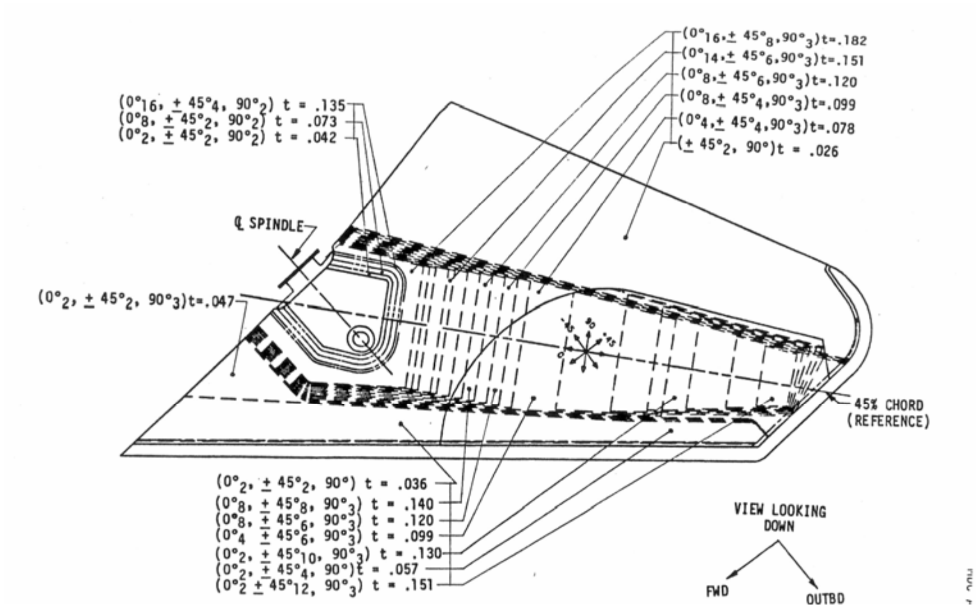

Figure 1: Schematic of F18 HS carbon/epoxy skin lay-up and thickness distribution.

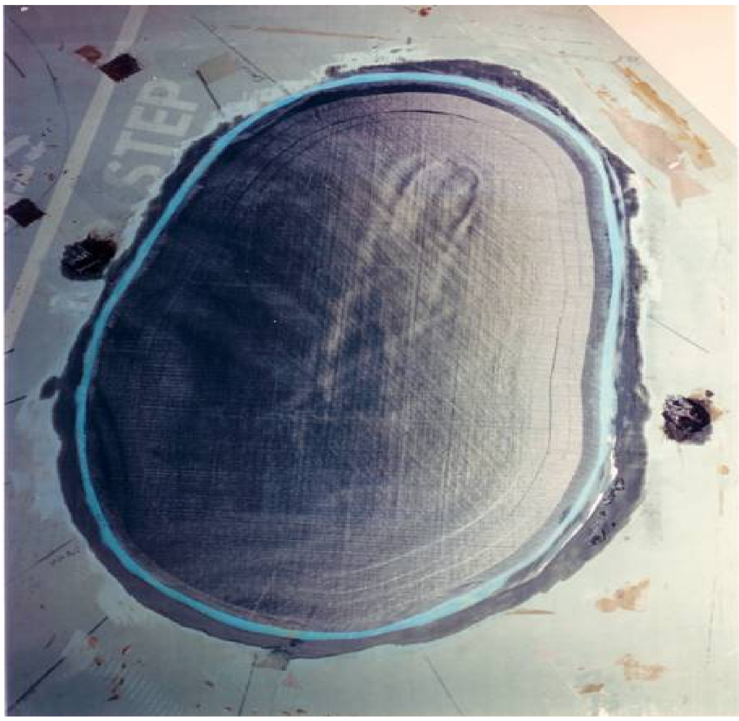

Figure 2: Scarf patch applied by the USN to the Australian F/A-18 HS, showing wrinkles

Figure 3: Formation of the scarf in the F/A-18 Horizontal Stabilator using a hand-held router

Figure 4: CNC Machined scarf cavity

Figure 5: CNC machined tool cavity

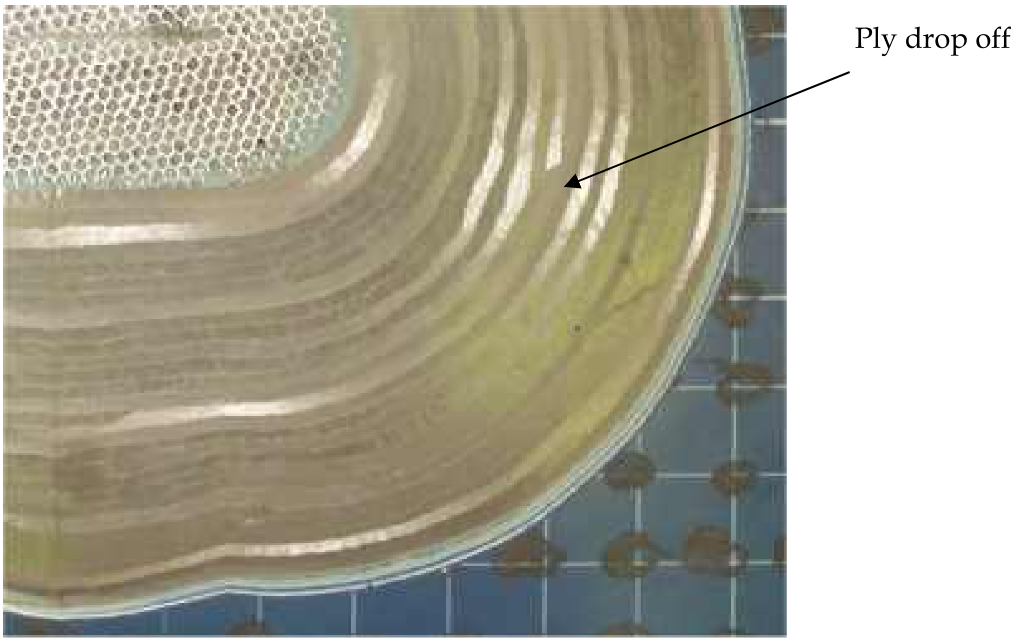

Figure 6: Visualisation of ply orientation and drop-offs in the machined cavity

Figure 7: Master Mylar template over pre-preg

Figure 8: Stabilator showing patch under a vacuum bag for evaluation of fit-up

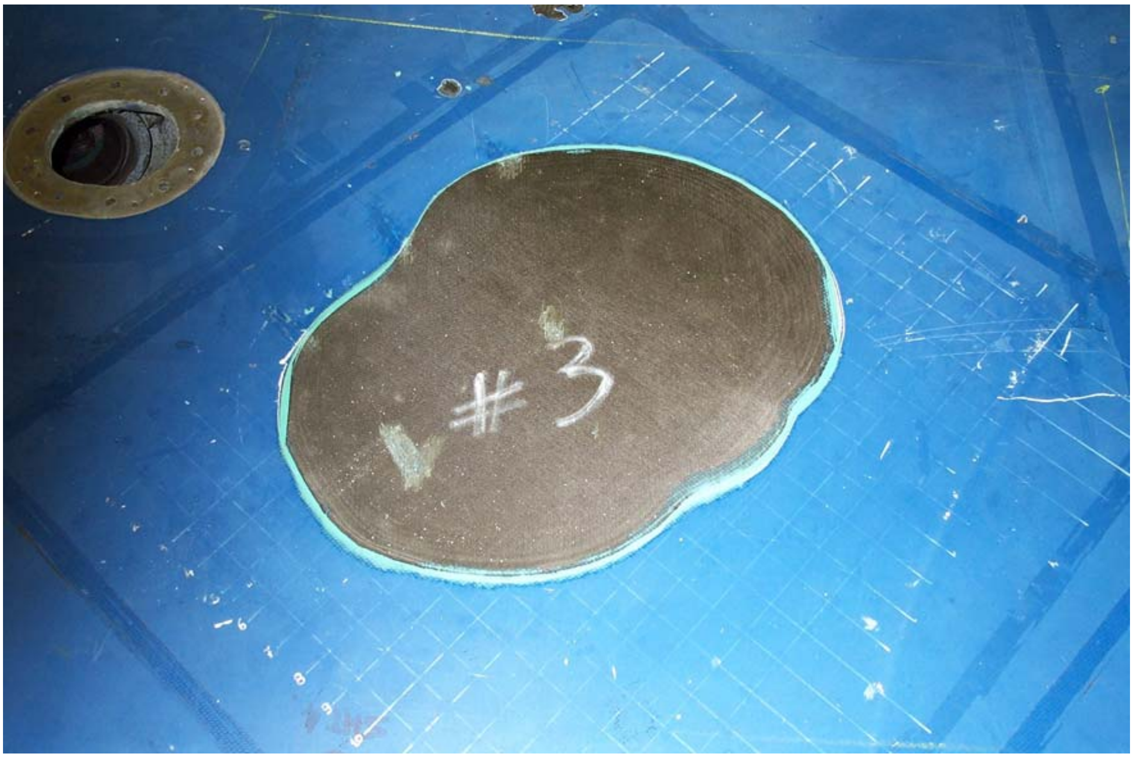

Figure 9: Patch bonded to HS

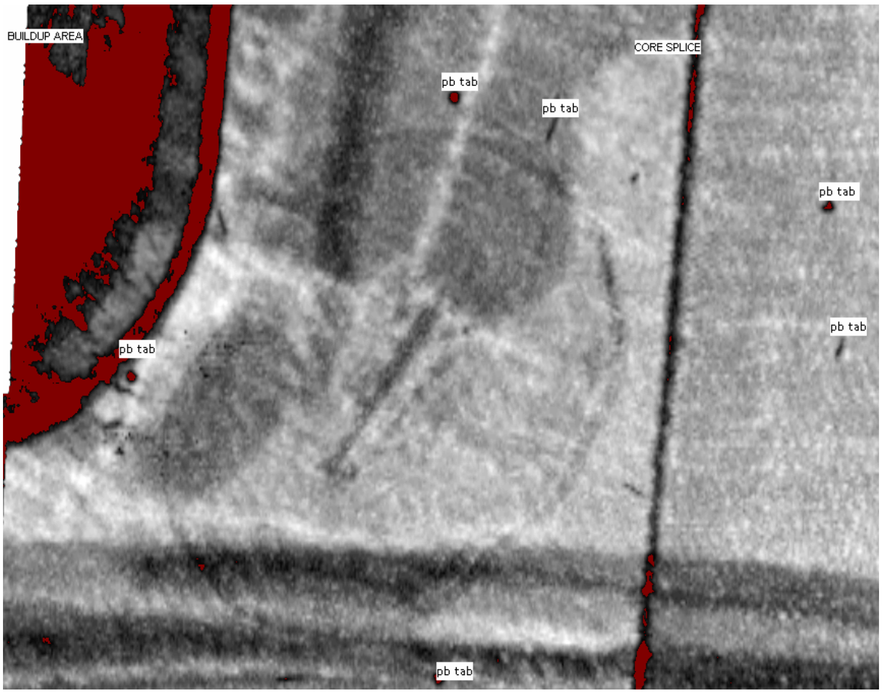

Figure 10: Ultrasound image of repair region.

Appendix A: Approaches to Increase Scarf Angle

A.1. Problem

Whilst it is highly desirable to increase scarf angle to minimise removal of parent material the severe hot/wet requirements and resulting low adhesive allowables in the case of aircraft with higher operating temperatures such as JSF may result in a requirements for a scarf angle even less than the conventional 3°.

The following list is a suggestion of some approaches that would increase scarf angle compared with the standard requirement:

1. Use a stiff external reinforcement (doubler) to reduce stress on the scarf joint. This approach is feasible only if significant surface profile changes are acceptable.
2. Make allowance for hole-edge strain allowables. This approach, which requires a 2D analysis of the strain at the edges of the repair hole, could allow use of a lower modulus patch. The strain allowables for filled holes with tapered edges need to be determined.
3. Make full allowance for bypass loads. This approach requires a full 3D F-E analysis of the repair situation and test validation at component level.
4. Use a multiple scarf configuration. This is a simple and highly effective design approach, but, unfortunately, presents severe implementation difficulties. Even a double scarf reduces scarf length by 50% for a given scarf angle.
5. Increase adhesive hot/wet strength. This is a prospect only if the failure mode in the adhesive is predominantly cohesive and the first (interface) ply failure mode in the composite occurs at a much higher level. This is a long-term prospect
6. Reinforce the bond line; however, the reinforcement would have to be strongly anchored through the parent and patch material and oriented at 45 ° to the bond line. This is also a long-term prospect.

Some of these possibilities, many of which could be combined, are briefly discussed in the following sections:

A.2. Analysis of Combined External Patch and High Angle Scarf

For a basic scarf joint :

$P = \tau \sin\theta \cos\theta / t$

Now the maximum load/unit width that the repair is required to carry is given by :

$P = Ee_u t$

$Ee_u t = \tau \sin\theta \cos\theta / t$

If we apply an external reinforceing doubler the load it carries is given by :

$Ee_u t_R$

Then :

$Ee_u t - Ee_u t_R = \tau \sin\theta \cos\theta / t$

Thus the thickness required for the external patch is given by :

$t_R = t(1 - \tau / Ee_u \sin\theta \cos\theta)$

On the basis of these equations, *Figure A1* plots the required patch thickness as a function of scarf angle for 3mm thick laminates assuming *E* = 70 GPa for parent material and reinforcing patch and assuming max τ = 8 MPa for adhesive FM 355 hot/wet.

This shows that the thickness of the external patch required to achieve a scarf angle of 3° is over 1.5 mm – which is half the thickness of the parent laminate; however, the thickness can be reduced in direct proportion to the stiffness of the doubler it could be reduced to less than 1 mm by using a highly orthotropic doubler .

A.3. Low Modulus Patch Approach, Based on 2D Effects

The low modulus-patch approach is broadly similar to that taken with bolted repairs in that the criteria for failure is that the allowable strain at the edges of the hole is not exceeded. Typical ultimate strains for open holes with 90 ° edges exceed 10,000 με. Thus the aim is simply to reduce the strain at the edge of the hole to an acceptable level without trying to fully restore strength or stiffness in the region. The low modulus patch could be used with a commensurately higher scarf angle as the loads to be transmitted by the adhesive are significantly reduced.

Figure A2 shows a theoretical plot of stress concentration Kt versus modulus ratio for a filled round hole with 90° edges in an isotropic plate. For stiffness ratio of 0.5 the allowable far field strain is less than 0.5 of that for the open hole (ratio zero) thus a far-field strain of 5000 microstrain would not be expected to cause failure. However, the starting Kt will be much higher for a hole with a scarfed edge – particularly with a low angle (~ 3°) scarfed edge.

A.4. Analysis of Adhesive System Strength Requirements

One way to achieve the above requirements is to increase the strength of the adhesive system. For the target of a 3^{o}-scarf the adhesive system hot/wet shear strength requirement is around 14 MPa. This compares with the current hot/wet strength of around 8 MPa for adhesive FM 355.

It may be feasible to increase adhesive strength up to this level, for example, through incorporation of nano-particles or reinforcements in the adhesive, although, this is a long-term R&D prospect.

A.5. Adhesive System Reinforcement

Assuming the loading is one direction (component in tension or compression) and it was possible to provide 45° reinforcement of the adhesive layer; the configuration can be modelled as a 0° laminate under tension/compression loading. The fibres need only to be oriented in the tension direction; the adhesive can react the compression loads. As this approach requires the scarf surface and patch to be pre-drilled, strength loss has to be considered.

The 45° orientation may be achieved by displacing the patch surface along the scarf prior to adhesive cure. A displacement equivalent to 100% strain is required.

The strength of the aramid fibre/adhesive composite will be dominated by the fibre strength then:

$$\tau = \sigma_f V_f = Ee_u / \sin\theta \cos\theta$$

$$V_f = Ee_u / \sigma_f \sin\theta \cos\theta$$

If the strength of aramid fibres is ~ 350 MPa (optimistic if the fibres are kinked), then the volume fraction required for 3 degrees scarf angle is 5%, with no allowance for the adhesive, as failure would be dominated by failure of the fibres.

Admittedly, this is a far-fetched proposal but could be worthy of investigation.

Nomenclature

Term	Definition
E	elastic modulus
e_u	ultimate design strain
E_x	elastic modulus in the primary loading direction
P	load transmitted by joint
t	laminate thickness
t_R	reinforcement thickness
V_f	volume fraction
ε	strain
θ	scarf angle
σ	direct stress
τ	shear stress

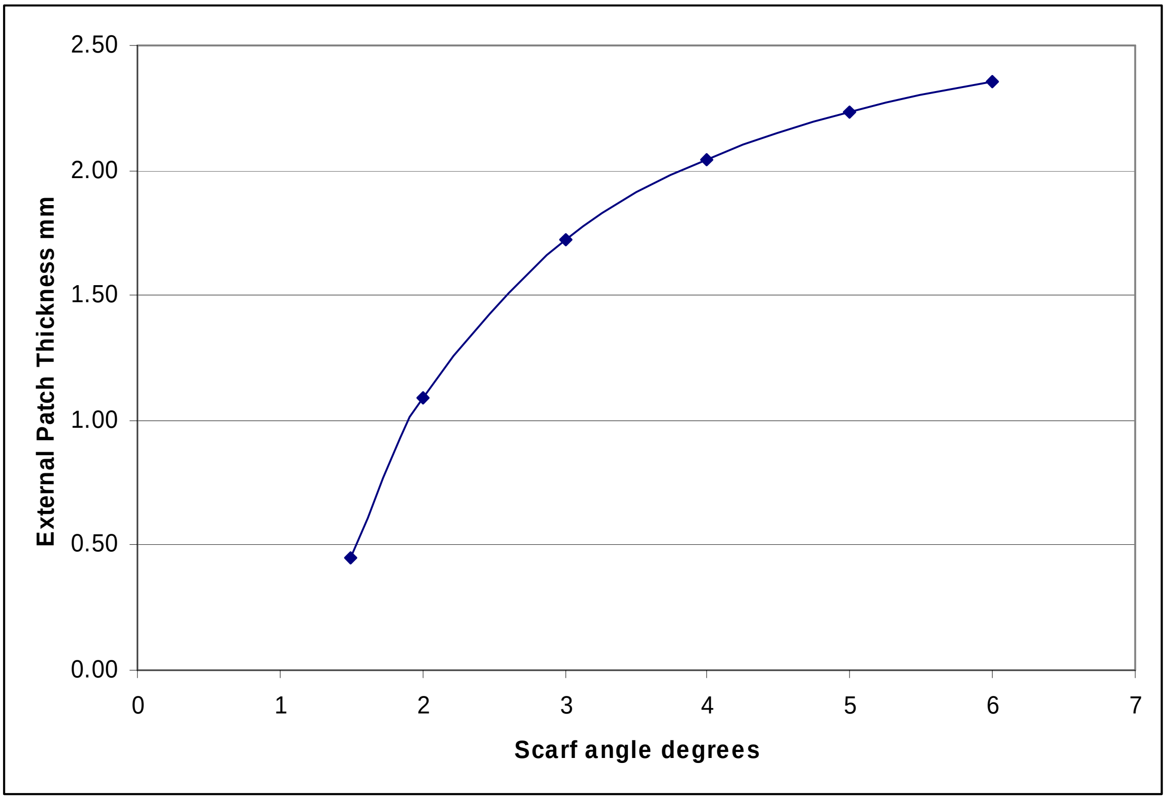

Figure A1: Required external patch thickness as a function of scarf angle for 3 mm laminate; the adhesive is FM 355 hot/wet.

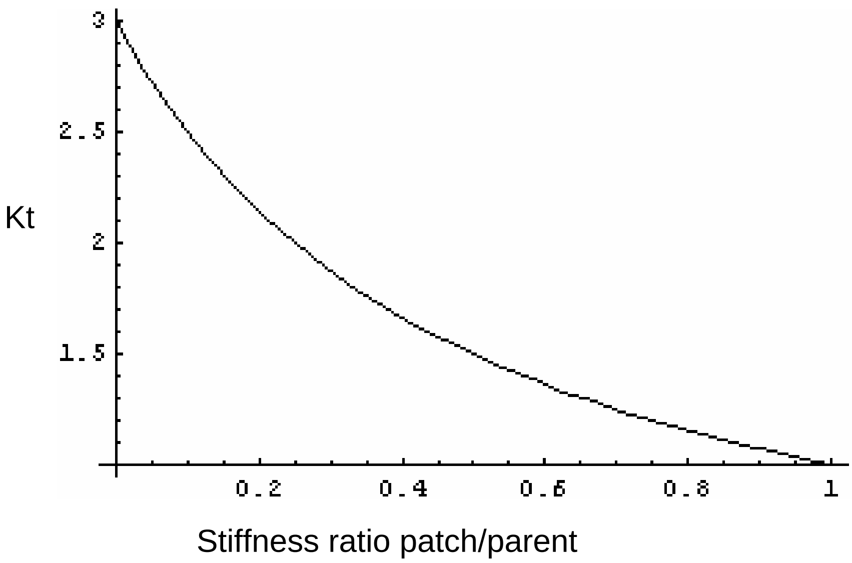

Figure A2: Plot of Kt versus modulus ratio for a filled hole; courtesy Dr Chun Wang

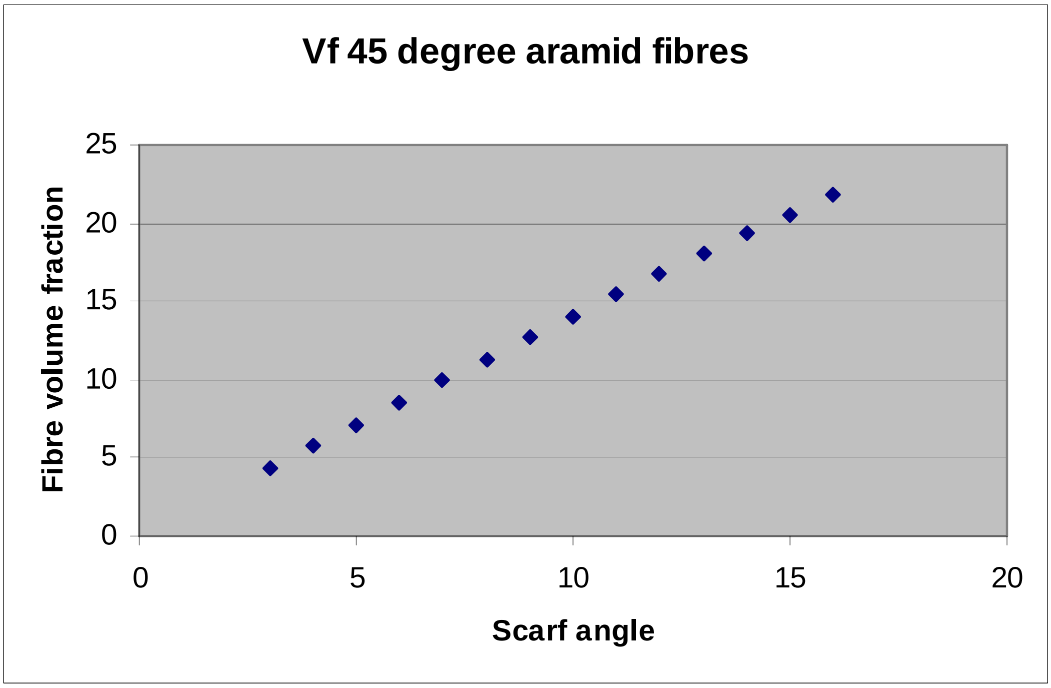

Figure A4:Plot of fibre volume fraction versus scarf angle, the fibres are notionally kinked to approximately 45°.

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Alan Baker

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19. ABSTRACT

The pre-moulded (hard) patch approach for scarf repair of composite structures has several advantages compared with the conventional prepreg lay-up (soft-patch) approach, which involves forming the patch directly in the repair cavity. These include the development of patch properties which match the parent structure; much improved patch geometry (no wrinkling or ply distortion) and, importantly for aircraft employing high temperature composites designed to operate at 177C/350F (such as JSF), reduced application temperature – depending on the repair adhesive chosen.
This report outlines a study aimed at developing this technology with potential for application on aircraft such as JSF.

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